

Final progress report: Development of global magnetosphere models of Jupiter

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Progress over the course of the grant period

Introduction

The objective of the proposal was to construct global magnetospheric models of Jupiter for the use of Jovian magnetospheric community. In the four years of the grant period we were able to achieve all of the stated science objectives. The work has resulted in (1) a new structural model of Jovian current sheet, (2) Global thickness map of the current sheet, (3) magnetic field models of the current sheet and (4) the global model of Jupiter's magnetospheric field including hinging and delay of the current sheet, sweep-back of the magnetic field and the shielding field of the magnetopause.

To accomplish our work, we assembled an exhaustive magnetic field data base from all of the spacecraft that have visited Jupiter (Pioneers 10 and 11, Voyagers 1 and 2, Ulysses and Galileo). The data were rotated into system III and JSM coordinates. We used the data at resolutions of 1 minute (for studies of the structure of the current sheet) and 10 minutes (for building the global model).

A new structural model of the current sheet

In this work, we analyzed magnetic field observations from all six spacecraft that have explored Jupiter's magnetosphere to determine the global structure of Jupiter's current sheet. We assembled a database of 6328 current sheet crossings by using an automated procedure which utilizes reversals in the radial component of the magnetic field to identify current sheet crossings. The assembled data base of current sheet crossings spans all local times in Jupiter's magnetosphere under differing solar wind conditions. The new model is based on a further generalization of the hinged-magnetodisc models of *Behannon et al.* [1981] and *Khurana* [1992]. Four new features of the improved model are that (1) close to Jupiter, the prime meridian of the current sheet (the direction in which it attains its highest inclination) is found to be shifted by 2.4° from the VIP4 model current sheet [Connerney et al., 1998]. (2) In addition to the delay caused by the wave travel time, the location of the current sheet is further delayed because of the sweep-back of the field lines. (3) The wave propagation velocity is seen to vary both with radial distance and local time and (4) The current sheet becomes parallel to the solar wind direction at large distances in the magnetotail. The new model is much superior at predicting current sheet crossing times than previously published models (especially in the midnight and dusk sectors). The RMS error of fit between the modeled and observed current sheet crossing longitudes is 19.4° . The results from this investigation have been submitted for publication to *J. Geophys. Res.* [Khurana and Schwarzl, 2004a].

Magnetic field models of the Jovian current sheet

In order to model the magnetic field of Jovian current sheet, we used analytical models of disk-shaped current sheets similar to those advanced by Tsyganenko and

Peredo [1994] for the Earth's current sheet. These models use an axially symmetric representation of the magnetic vector potential of a ring current to provide simple expressions for the calculation of magnetic field. Because the solutions are self-similar, several basic-modes can be constructed, each describing a ring current with different rate of outward decrease of the current density. The basic mode solutions are then combined in required proportions and fitted by least squares to the magnetic field observations. The basic equation describing the vector potential of a current sheet mode is

$$A = \sum_{i=1}^N f_i \int_0^{\infty} J_1(\lambda \rho) \exp[-\lambda(\beta_i + |z|)] \cdot \sin(\beta_i \lambda) d\lambda = \rho \sum_{i=1}^N f_i \frac{t_i (1-t_i^2)^{1/2}}{S_{1i} S_{2i}} \quad (1)$$

$$\begin{aligned} S_{1i} &= [(\beta_i + |z|)^2 + (\rho + \beta_i)^2]^{1/2} \\ \text{where } S_{2i} &= [(\beta_i + |z|)^2 + (\rho - \beta_i)^2]^{1/2}, \\ t_i &= \frac{2\beta_i}{S_{1i} + S_{2i}} \end{aligned} \quad (2)$$

The coefficients f_i and b_i describe the strength and the profile of the current density in each of the modes. The models can be modified to include the shape of the current sheet and its thickness by replacing the term z in equations (1) and (2) with the term ζ where,

$$\begin{aligned} \zeta &= z - z_{cs} & z > D \\ \zeta &= 0.5((z - z_{cs})^2/D + D) & z < D \end{aligned} \quad (3)$$

Here, $z_{cs}(X, Y)$ is the model location of Jupiter's current sheet (describing its shape) and D is its half thickness.

Global thickness map of Jupiter's current sheet

A cursory examination of the radial component of the magnetic field in Jupiter's magnetosphere showed that the motion of the s/c into and out of the current sheet is rapid in the dawn sector and quite gradual in the dusk sector (see Figure 1 below). This observation suggests that the current sheet thickness is a function of local time.

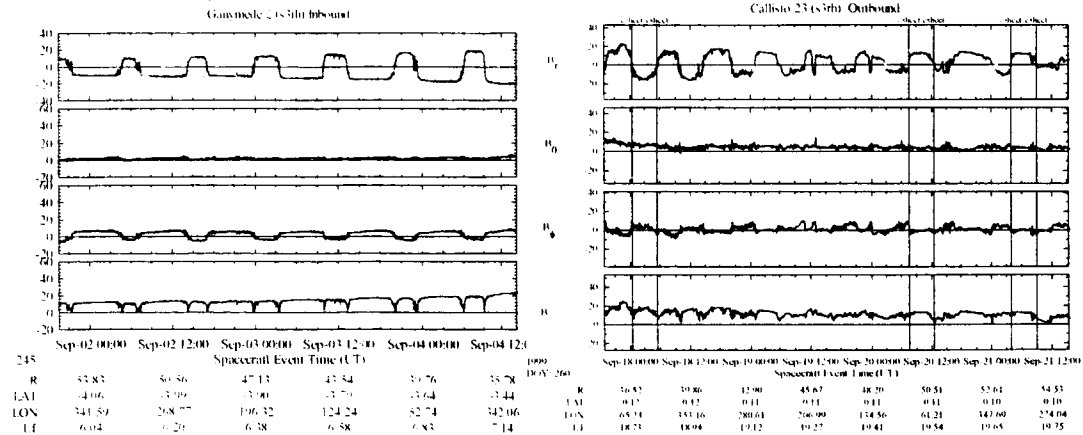


Figure 1 Magnetic field observations from Galileo in the dawn sector (left) and the dusk sector (right). The radial distance covered by the spacecraft in both the figures is 35-55 R_J .

In order to quantitatively obtain the current sheet thickness in all local times, we subdivided the magnetic field data into 12 local time bins and two radial distance bins ($< 25 R_J$ and $> 25 R_J$). We then fit the magnetic data from each local time and radial distance bin with equations (1) –(3) to obtain the strength of each mode and the thickness of the current sheet for each bin. The resulting fits showed that the current sheet varies in half-thickness of $2 R_J$ in the dawn sector to $4.5 R_J$ in the noon sector. We are currently preparing a manuscript highlighting these results in the Journal of Geophysical research [Khurana and Schwarzl, 2004b)

The new global model

We have now obtained a new global model of Jupiter's magnetospheric field which borrows techniques and methods used by modelers for the earth's magnetosphere. Our model consists of modules which specify (1) the internal spherical harmonic model (VIP4, Connerney et al., 1998), (2) the ring current and the magnetotail current system (using equations 1-3 above.), (3) the field from the radial current system which reinforces corotation of the outflowing plasma. (4) the shielding fields from an axially symmetric magnetopause (5) and the interconnection magnetic field between solar wind IMF and the magnetosphere.

We used Tsyganenko's [1998] technique of introducing general deformation to model the sweep-back of the field lines resulting from the radial current system. In the general deformation technique, the transformation is performed by replacing the original coordinate system (f, g, h) by a deformed one, (ξ, η, ζ) , which are known smooth functions of the original coordinates. The deformed field is defined as:

$$\mathbf{B}'(f, g, h) = \nabla \alpha(\xi, \eta, \zeta) \times \nabla \beta(\xi, \eta, \zeta) \quad (4)$$

The most important property of this transformation is the possibility to explicitly relate the components of the deformed magnetic field \mathbf{B}' to those of the original field \mathbf{B} by a linear transformation, so that

$$\mathbf{B}' = \hat{\mathbf{T}} \mathbf{B}^* \quad (5)$$

The transformation matrix is fully defined via the partial derivatives of (x, h, z) with respect to (ξ, η, ζ) , which are known functions and chosen in accordance with the desired properties of a specific deformation.

We apply a stretch transformation that implements the idea behind equation (5). Thus, we stretch the ϕ coordinate by an amount proportional to the radial distance:

$$\Delta \phi = -p \left(1 + q \tanh^2 \frac{z}{D_2} \right) \rho \quad (6)$$

This transformation results in a sweep-back of the field lines.

To shield the dipole, we use the cylindrical harmonics of the form:

$$\begin{aligned} U_{\perp} &= \sum_{i=1}^N A_i J_1 \left(\frac{\rho}{b_i} \right) \exp \left(\frac{x}{b_i} \right) \sin(\phi) \\ U_{\parallel} &= \sum_{i=1}^N C_i J_0 \left(\frac{\rho}{d_i} \right) \exp \left(\frac{x}{d_i} \right) \end{aligned} \quad (7)$$

where the first term shields the perpendicular and the second term shields the parallel component of the dipole. We get excellent results by using terms up to $N=4$ and specifying that B_n through the magnetopause be zero.

To shield the field of the current sheet, we chose to use the Cartesian harmonics of the form: (with $n=8$)

$$U = \sum_{i=1}^N \sum_{k=1}^N a_{ik} \exp \left[\sqrt{\frac{1}{\rho_i^2} + \frac{1}{\rho_k^2}} \right] \begin{Bmatrix} \cos \frac{y}{\rho_i} \\ \sin \frac{y}{\rho_i} \end{Bmatrix} \begin{Bmatrix} \cos \frac{z}{\rho_k} \\ \sin \frac{z}{\rho_k} \end{Bmatrix} \quad (8)$$

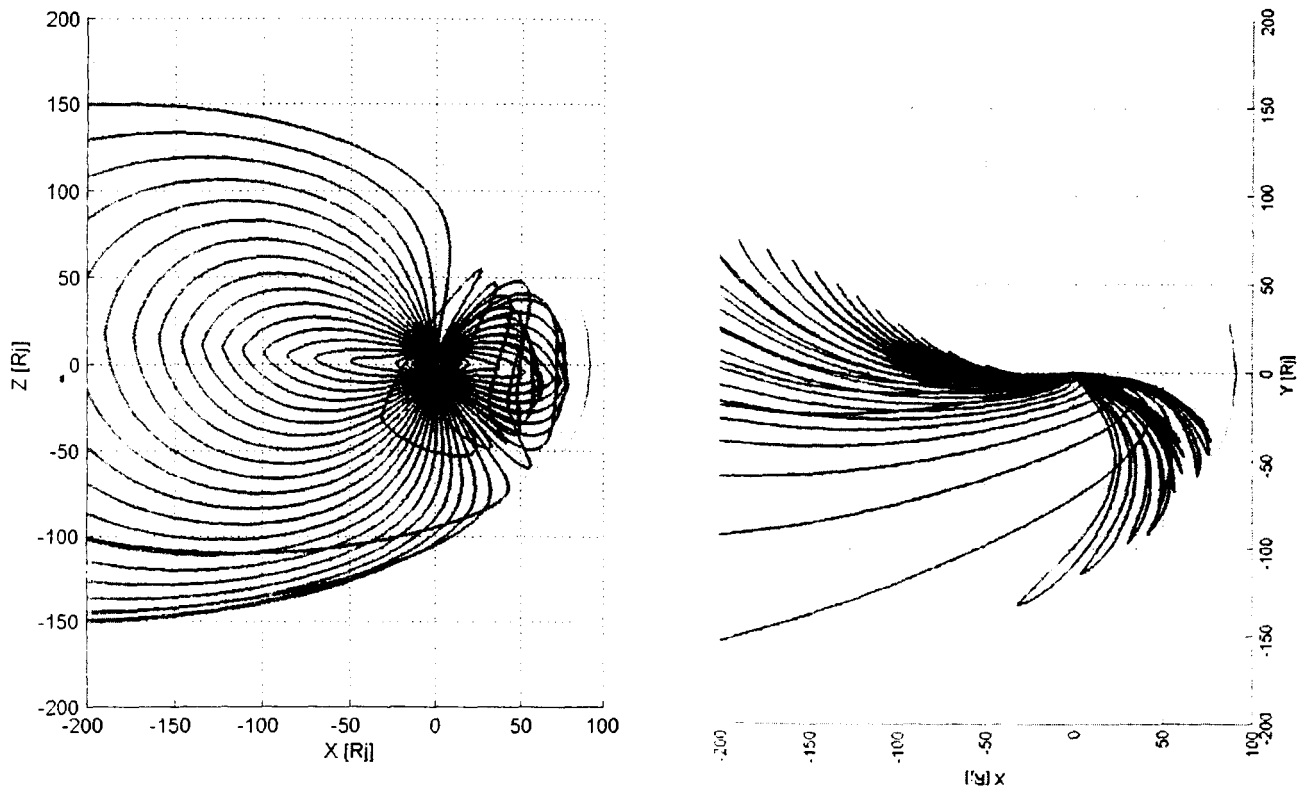


Figure 2 Some representative field lines from the magnetospheric model of Jupiter in the noon-midnight meridian view (left) and polar view (right). All field lines originated in the noon-midnight meridian but had magnetic latitudes ranging from 20 degrees to 90 degrees.

To build the model, we used data from all of the Galileo orbits and from all the five previous spacecraft that have visited the magnetosphere of Jupiter. Figure 2 shows some representative field lines in the magnetosphere of Jupiter. The sweep back of the field lines is clearly visible in the polar view. The field lines also show the effect of a hinged-warped current sheet near the equatorial region. We are currently writing up this work into a manuscript to be published in *Journal of Geophysical research* [Khurana et al., 2004]. Many aspects of these investigations were also published in an invited review chapter in Khurana [2004].

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Research articles resulting from this investigation

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- Khurana, K. K., H. K. Schwarzl, The global structure of Jupiter's magnetospheric current sheet, Manuscript submitted to *J. Geophys. Res.*, 2004a.
- Khurana, K. K., H. K. Schwarzl, The local time and radial variations of the thickness of Jupiter's current sheet, Manuscript under preparation, to be submitted to *JGR*, 2004a.
- Khurana, K. K., N. A. Tsyganenko, A new magnetic field model of Jupiter's current sheet, Research paper under preparation. Manuscript to be submitted to *J. Geophys. Res.*, 2004a.

Talks presented at scientific meetings

- Khurana, K. K. and N. A. Tsyganenko, A Magnetic Field Model of Jupiter's Current Sheet From Galileo measurements, Talk presented at the fall AGU meeting, San Francisco, 2001.
- Khurana, K. K. and N. A. Tsyganenko A Global Model of Jupiter's Magnetospheric Field, paper presented at the fall AGU meeting, San Francisco, 2002.
- Taylor, D. J., K. K. Khurana, and M. G. Kivelson, A new model of the structure of the neutral current sheet of the Jovian magnetosphere, paper presented at the fall AGU meeting, San Francisco, 2002.
- Khurana, K. K. and N. A. Tsyganenko, Towards a global magnetic field model of Jupiter's magnetosphere derived from observations of Galileo and previous missions, Paper presented at the spring AGU-EGS meeting held in Nice, France, 2003.
- Khurana, K. K., N. A. Tsyganenko and H. K. Schwarzl, A New Jovian Magnetospheric Field Model for Galileo and Jupiter Icy Moon Orbiter (JIMO) Missions, paper presented at the Fall AGU meeting, San Francisco, 2003.
- Khurana, K. K. and H. K. Schwarzl, The local time variations of Jupiter's current sheet Location and Thickness, Paper presented at the spring meeting of the AGU held in Montreal, Canada, 2004.
- Khurana, K. K., N. A. Tsyganenko and H. K. Schwarzl, A model of Jupiter's global magnetospheric field: Construction and comparison with data, paper presented at the COSPAR meeting in Paris, 2004.